IMPLICATIONS FOR ITER CODAC
FROM DIII-D EXPERIENCE

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D. GATES,† S.H. HAHN,‡ G.J. McARDLE,¶ A.A. SQUITIERI,* and B. XIAO§

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*University of Wisconsin-Madison, Madison, Wisconsin.
†Princeton Plasma Physics Laboratory, Princeton, New Jersey.
‡National Fusion Research Institute, Daejon, Korea.
¶Culham Science Centre, Abingdon, United Kingdom.
§Academica Sinica Institute of Plasma Physics, Hefei, China.

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Abstract

The DIII-D digital plasma control system (D3PCS) has been in use since 1993 controlling DIII-D plasmas. Control research and D3PCS development at DIII-D has revealed aspects of advanced tokamak control which can help inform the ITER design. The D3PCS has also been adapted for use at several fusion devices worldwide, which has allowed the DIII-D team to obtain a significant understanding of common requirements for plasma control on multiple fusion devices, along with substantial experience in the alternative computing, data acquisition, and networking technologies presently available.

We describe some of what has been learned and highlight the relevance of these lessons for ITER CODAC. Several capabilities of the D3PCS are described in the context of ITER requirements. This description touches on multiple subsystems described in the CODAC conceptual design. We also discuss features of D3PCS architecture that are appropriate for today's experimental devices but may not be appropriate for ITER, which requires a much more comprehensive system for ensuring device safety. Even for these applications, the knowledge gained in implementing methods to aid in ensuring device safety on present devices provides useful guidance for an eventual ITER solution.
1. Introduction

The DIII-D Plasma Control System (D3PCS) [1] is a hardware and software application that is used to control and monitor tokamak plasmas. It is deployed at fusion experimental sites in the U.S. (DIII-D, NSTX, MST, PEGASUS), the U.K. (MAST), China (EAST), and South Korea (KSTAR) [2]. Since 1993, the D3PCS has been used in DIII-D experimental operations to stabilize various instabilities [vertical, resistive wall mode (RWM), neoclassical tearing mode (NTM)] and to control plasma characteristics such as plasma current, shape, position, beta, rotation, and profiles of density, temperature, and current. During that time, the D3PCS has evolved with the demands of the experimental program.

We describe some of what has been learned through use of the D3PCS on DIII-D and other devices and highlight the relevance of lessons learned for the ITER Control, Data Acquisition, and Communication (CODAC) system [3]. We also discuss features of the D3PCS architecture used on today's experimental devices that may not be appropriate for ITER.
2. Architecture of the D3PCS

Figure 1 shows a block diagram of the functionality provided by the D3PCS divided between software that defines the desired evolution of the plasma discharge (purple outline) and software that runs in real time during a discharge to control the plasma (red outline). The simulation server (simserver) is separate from the D3PCS and is used to test correctness of algorithm execution.

The waveform server (waveserver) serves as central storage for information defining the desired shot evolution. Operators interact with a user interface program to input parameters and time dependent waveforms that define the desired evolution. More than one interface may execute simultaneously, each communicating with the waveserver to store and display programmed discharge information.

The lockout server (lockserver) synchronizes setup and execution of the real time processes with tokamak machine control and the plasma discharge. Host realtime processes, one for each real time process, load the realtime code and data onto the real time CPUs just prior to the discharge. During discharge preparation, status information is transmitted from the D3PCS to a message server, which displays them for the operator.

Each block in Fig. 1 represents a software process, which does not necessarily map one-to-one to a separate hardware CPU. More than one process can execute on a single CPU and, occasionally, one process can execute on multiple CPUs. For example, real time EFIT equilibrium reconstruction [4] uses multiple CPUs.

Pulse Programming. Any plasma control system must provide an interface through which to specify the desired evolution of the plasma and device systems. A period of time for control programming in the interface is called a segment in CODAC [3] and a phase in the D3PCS. A CODAC segment chain is called a phase sequence, i.e. sequence of phases, in the D3PCS. Figure 2 shows an example D3PCS operator interface (segment editor in CODAC). Desired time evolution of plasma parameters is specified by editing vertices (time/parameter pairs) in reference waveforms. These points are interpolated during real time execution to define a reference for the control algorithm. The shaded region on the right of the waveform window indicates that the system is controlled by a different phase at that time, so the waveform in that region does not affect the control. A menu of parameters to be controlled is on the left.
Fig. 1. Block diagram of D3PCS and Simserver software processes.

Fig. 2. User interface for the EAST PCS. A reference signal for PF coil 1 is shown.

The D3PCS has a slightly different hierarchy than that proposed for ITER. In the D3PCS, actuators are (roughly) grouped into categories, for each of which a sequence of time segments (phases) is defined. Editing the phase includes selection of the control algorithm (and its reference set) to execute during the phase, programming of desired evolution of controlled quantities, and setting of parameter data that modifies algorithm
behavior. Initial D3PCS execution brings up default algorithms. Selecting an algorithm provides default parameter settings.

Data can also be loaded from a previously executed pulse or prepared setup. This type of operation more closely matches the envisioned preparation for ITER pulses [3], where segments are prepared at experimental sites, then loaded into the ITER operational system after multiple evaluations and approvals. The D3PCS operator can restore an entire previous discharge or labeled setup or select a subset of data, in which case the interface in Fig. 3 is used.

The stored data has an hierarchical structure, where high to low nodes proceed from left to right in Fig. 3. Highlighting a node in any column causes the corresponding lower level nodes to be displayed in the columns to the right. Pressing "load selected" loads all data for that node as well as all data in the lower branches.

The hierarchical structure concept is relevant for ITER, but the specific hierarchy in D3PCS may not be appropriate. For example, category (see Division of Actuator Authority below) is at the top of the D3PCS hierarchy while for ITER, it might appear below phases, if it is even a useful concept for ITER.

The waveserver performs simple rules checking (e.g. potential conflicts between algorithms or missing data required to execute properly) when storing data from the user interface. Violations cause the “data” button in the upper right hand corner of Fig. 2 to turn red and pulse execution is not allowed. Operation limits are enforced at the interface by not allowing operators to select vertices in upper and lower cross-hatched regions of the waveform window, shown in Fig. 2. During data loading, as in Fig. 3, these limits are not enforced but violations will turn the “data” button red.
In Fig. 1, only one waveserver is shown. The proposed CODAC architecture would require multiple copies of something like a waveform server — one at each experimental site and one inside the Plant Operating Zone [3,5].

**Division of Actuator Authority.** D3PCS algorithms are grouped by category. In most cases, a category corresponds to authority over a set of actuators, which means only one of the algorithms may execute at a time; selection is made by the operator loading an algorithm into a phase. In existing devices, there is heavy reliance on “decoupled” control where coupling between control parameters is treated as a disturbance, which is consistent with this actuator separation approach. Suppressing disturbances requires additional actuator effort, which challenges the relevance of this approach for ITER, since much more control integration is needed to make effective use of limited actuator authority. There is little operational experience with large-scale plasma control integration, however, which raises the issue of how to organize algorithms in the ITER plasma control system (PCS). This issue is raised in [3], which apparently assumes no restrictions on algorithm use of actuators, except to detect potential conflicts.

Perhaps more problematic is shared use of actuators for multiple control purposes. For example, the electron cyclotron (EC) system is claimed for use by NTM stabilization, profile control, plasma heating, sawtooth control, and (potentially) toroidal Alfvén eigenmode (TAE) control. Non-axisymmetric coils are claimed for control of error fields and RWM, suppression of edge localized modes (ELMs), and perhaps rotation control. To support shared use of actuators at DIII-D, additional categories have been created so that they no longer map one-to-one to actuator sets and switching of actuator purpose is pre-programmed at the interface. ITER requires intelligent real-time switching, which may also trigger a need for a bumpless transfer mechanism (see below), since it represents a change of control algorithm.

**Switching of Phase Sequences.** ITER switching between segment chains (phase sequences) will be asynchronous [3], in contrast to present D3PCS use, where asynchronous switching is the exception. Most asynchronous switching in D3PCS is used for responding to off-normal events (see below), but there are cases where it is used to provide condition-based switching of algorithms as part of an experiment. The D3PCS method used for asynchronous switching is now being modified to support an expanded effort on development of fault detection and response scenarios [6]; this mechanism may be appropriate for ITER.

**Bumpless Transfer.** Switching from one control algorithm to another during a pulse can initiate a “bump” in control, i.e. a period when control is relatively poor. Two sources of this bump are a mismatch of reference and actual values of a controlled parameter at the transfer time and use of a control algorithm with memory that is not properly...
initialized. An algorithm has memory if its response depends on previous sample times in addition to the current time. The majority of modern model-based controllers are of this type.

Several methods have been used in the D3PCS for smoothing this transfer, including: (1) matching of reference signals at the transfer time by the operator, (2) setting the initial value of feedback gains to zero at transfer time, then ramping back up to full controller gain, (3) setting the initial value of the reference equal to the measured value at the transfer time, then ramping that reference to coincide with the pre-programmed reference, (4) shared control of actuators, with the fraction of control given to the new algorithm gradually changed from zero to 100 percent. None of these has been completely satisfactory. The issue with (1) is that control is assumed to be good prior to the transfer time and it can require expert operator programming if control parameters differ between the old and new algorithms. Methods 2 through 4 do not provide full control during the transition period. It's not clear if any of these methods are applicable to re-purposing of actuators during the pulse (see Division of Actuator Authority).

A special segment called a transition is proposed in [3], whose purpose is to smoothly transition between two consecutive segments. This approach addresses the problem of mismatched reference and actual parameters (if control is good in the transition), since reference signals are calculated in real time to ensure matching parameters. The most effective methods for initializing algorithms with memory require calculations on data prior to the algorithm change. A simple example is use of a filtered version of a noisy parameter to initialize. One possibility for addressing this need in ITER PCS is to provide a “hook” in transitions that allows calculation-only functions from the follow-on segment to be executed.

**Off-Normal Events or Faults.** The issue of off-normal event and fault (ONF) system architecture for ITER is complex, because of the large number of potential faults and responses and the condition-dependent nature of those responses. For example, proximity to a stability boundary may trigger a switch to an avoidance response by the ONF system. If successful, the ONF system would need to switch to a recovery scenario to return to nominal operation. If not, the system might trigger a soft shutdown response, then perhaps a fast shutdown response, every one of these changes of response requiring some customization based on selecting the most appropriate response scenario for the present state of the system.

The architecture for asynchronous switching in D3PCS can support arbitrary chains of response scenarios, but has not been used in such a complex manner. In fact, the present approach is rather cumbersome for large numbers of response scenarios, so a more flexible method is being implemented that is consistent with the data-driven
philosophy of [3]. A description of fault detection and response actions used at devices using the D3PCS and an overview of the system under development is given in [6]. The proposed architecture may be appropriate for ITER, but real evaluation can only occur once the number of ONF tests and responses implemented in D3PCS becomes representative of the system required for ITER. Substantial effort is needed in the next few years in the fusion community to develop these responses.

**Current vs. Voltage Actuation for Shape, Position, and \( I_p \) Control.** A topic not often discussed is the relative advantage of using voltage-regulated or current-regulated PF power supplies. A current-regulated supply, apparently preferred by power supply designers, prevents commanding power supply voltage directly. A voltage-regulated supply allows either voltage actuation or current actuation using an optional current control feedback algorithm within the PCS. The ability to do both has been critical for operation of EAST and KSTAR, because current feedback control is not able to regulate coils well enough to ensure simultaneous field null quality and specified loop voltages for breakdown. These devices, like ITER, have no ohmic coil; errors in ohmic coil current control do not significantly degrade a breakdown null configuration.
3. Hardware Issues

The D3PCS overall hardware architecture mirrors the plans for ITER [3], but ITER is likely to differ in details. DIII-D has the largest system among devices using the D3PCS, but all have similar hardware architectural features [7]. Like DIII-D, ITER will use a distributed system with fast real-time network(s) to transfer data from diagnostics to multiple real-time processors and between processors and actuators. It will emphasize use of COTS hardware, acquire a large number of diagnostic signals, and command large numbers of actuators. However, control timescales will be significantly longer for ITER and real-time hardware significantly faster. ITER will require fast streaming for archiving long pulse data, while DIII-D real-time streaming is limited to control room display data; current work on the EAST and KSTAR versions of D3PCS aims to implement continuous archiving. ITER will need to support multiple complex real-time physics calculations such as Grad-Shafranov equilibrium reconstruction [4] in the D3PCS. Both DIII-D and ITER aim to minimize the mixture of hardware to reduce maintenance, but hardware is always mixed during upgrades, so both architectures must support this evolution.
4. Remote Participation

Support of EAST and KSTAR has defined our primary needs for remote participation tools to date. Most ITER-relevant issues that arise are already well documented. An issue not often emphasized is the need for adequate network bandwidth between the device and remote sites. For example, the connection from GA to EAST uses a tiny portion of a high-energy physics network; the lack of dedicated bandwidth causes problems for remote support.

In addition to experimental participation, remote operators need to participate in programming of pulses, which imposes a more demanding security requirement. A method is described in [3] for remote development of a pulse that can be uploaded at the ITER site. An additional challenge for our work is adequate access control when remotely programming the immediate next pulse and sharing access with operators onsite. These require additional technical solutions [5] and tighter coordination with onsite personnel.
5. Modeling for Control

The reduction of actuator control margins due to cost and the demand for provable performance lead to strong demands for model-based control in ITER. This implies the need for sufficiently accurate models of all relevant systems, including plasma response, diagnostics, instrumentation, and actuators. The concept of “model” is often different for control designers and those responsible for plasma physics exploration, diagnostics, and actuator systems. In addition, the request for a control model is often viewed as a distraction from efforts to get a subsystem working or operate it experimentally. As a result, a realistic model is almost never obtained until long after the subsystem is in routine use. We see a potential difficulty for ITER, where control algorithms must be validated with realistic models before being allowed to control a plasma, along with a potential additional problem that, after system delivery, industrial suppliers may have no motivation for providing such a model. The system self-description required of suppliers [3] is intended to support model development but seems to place responsibility for the models onto the control team. We recommend that both control-level and simulation-capable (more detailed, including nonlinear effects) executable models be required as part of delivery of each subsystem. This requirement should also specify a level of prediction accuracy of system output response to inputs.
6. Controller Implementation in D3PCS

To construct a control algorithm in the D3PCS requires generating a number of standardized format code and data structures plus a few free-format real-time calculation functions. A number of C-preprocessor macros are provided with the D3PCS distribution to automate much of the data structure generation. Self-describing control parameter data allow construction of generic codes that can be driven by many different types of parameter data. Storrs and McArdle [8] have taken these ideas one step further and developed an XML tool that parses a set of XML “requirements specification” documents to generate the standard data structures and associated code needed to construct one of these algorithms. This tool seems to represent a step toward the ITER vision of “data-driven” control algorithms.

Our understanding of how to develop and maintain fusion plasma control systems has evolved considerably since the D3PCS was first fielded and continues to evolve as improved methods for control algorithms and software are attempted and validated. Given the immaturity of fusion plasma control relative to ITER requirements, it is likely this understanding will continue to evolve through ITER’s lifetime; this evolution should be accounted for in the design and long-term plan.
7. Verification and Validation (V&V)

There are two main requirements for V&V of control algorithms in the ITER PCS:

1. test that the algorithms have been properly implemented in the PCS (verification),
2. test that the algorithms effectively control the plasma (validation).

Validation of control effectiveness is usually done with simulations. Initial validation can use simple models, but final evaluation should use a more realistic system model, including delays due to the real time implementation environment, which has been validated against experimental data.

Final testing of many D3PCS algorithms are performed using the simserver (Fig. 1) capability [9], shown in Fig. 4. In test mode, the real time code is executed on parallel real time computers or serially on a single computer and communicates with a simulation of the tokamak. This closed loop execution verifies both algorithm effectiveness and correct implementation in the real-time code. When testing is complete, I/O paths are switched to control plasmas on the actual device. This kind of simulation tool is envisioned for multiple purposes in CODAC [3], including V&V of controllers implemented in PCS, operator training, and validating the pulse schedule.

![Fig. 4. Connection of a simulator to D3PCS.](image)

The same data exchange mechanism is also used to perform open-loop tests of the D3PCS by operating on archived experimental or simulated data, for initial testing of code or re-validation after modifications are made.
The closed loop simulation capability has been used for V&V of DIII-D, KSTAR, and EAST algorithms prior to use on the device, for developing programmed waveforms and controller gains for DIII-D, and is now being adapted for use as a training tool for new KSTAR operators. All EAST and KSTAR algorithms were tested with the simserver before initial use in operations. The RTEFIT reconstruction and isoflux control, a very complex set of calculations, was customized for the EAST PCS with development and validation done with simulations. It was then implemented at EAST and within 2 weeks was providing effective shape control for EAST plasmas.

There are some issues ITER should keep in mind when using this method of V&V. First, the simserver is not guaranteed to find all implementation errors. For example, an uninitialized variable in an EAST algorithm was not detected during simserver testing nor during initial use in operation, since such variables can be randomly initialized. We also expect difficulty in correctly emulating time delays in the ITER simulation system. The primary issue relevant to ITER is the fact that simulations simply cannot generate accurate output data in response to inputs as fast as the actual device and plasma.
8. Conclusions and Recommendations

In this paper, we have examined several features of the D3PCS in the context of ITER needs. This examination benefited greatly from comparing and contrasting with portions of the CODAC conceptual design [3]. Before a detailed design can begin, there must be final decisions made about how ITER will operate (concepts for which are outlined in [3]) and what will be controlled. The design can benefit greatly from experience and knowledge at present devices, but requires some synthesis of common functional requirements from this experience, as well as identification of how and why different approaches were taken to solve certain common problems and their relevance to ITER needs.
References

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